

## **Absorption Enhanced Liquid Ablation with TEA CO<sub>2</sub> Laser**

**Enrique Sterling, and Andrew V. Pakhomov,**  
*University of Alabama in Huntsville,*  
*Huntsville, Alabama USA 35899*  
[\\*pakhomov@email.uah.edu](mailto:*pakhomov@email.uah.edu);  
256 824 2830; fax ext 6873

**C. William Larson, and Franklin B. Mead, Jr.**  
*Propulsion Directorate, Air Force Research Laboratory,*  
*Edwards AFB, CA 93524-7680, USA*

### **Abstract**

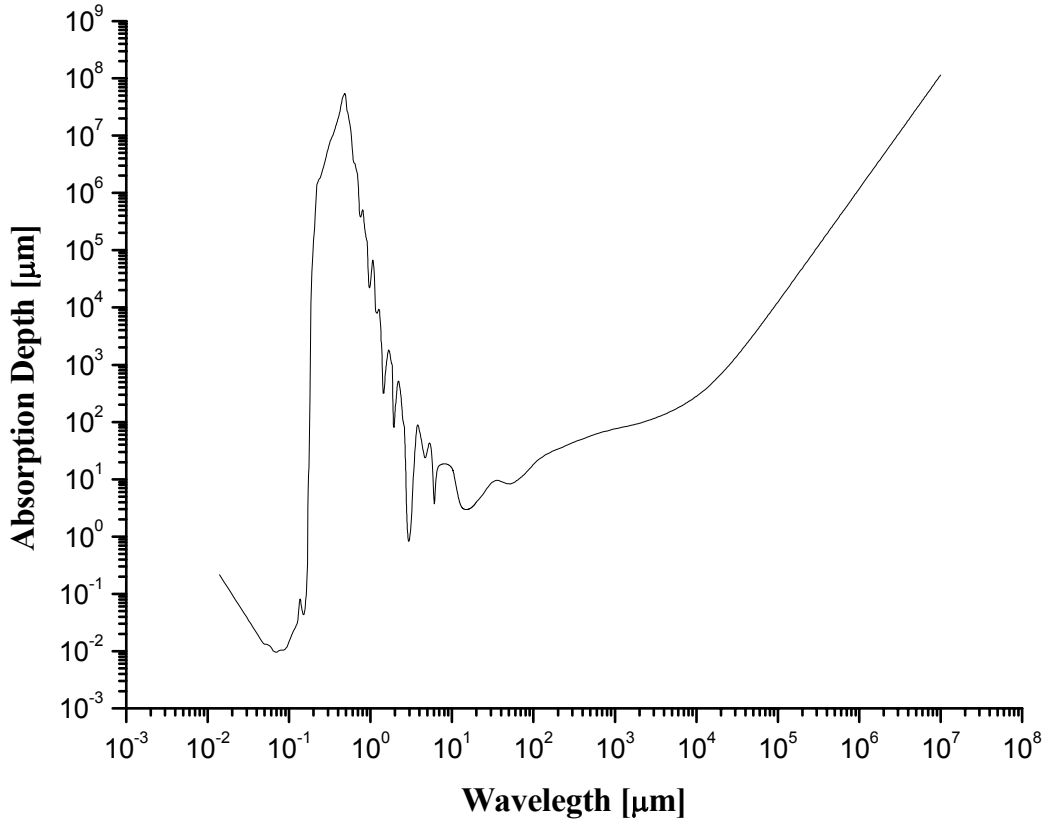
A novel technique for measuring of force as a function of time was developed for the study of enhanced momentum transfer in laser-ablated water solutions of Sodium Tetrafluoroborate [NaBF<sub>4</sub>], a compound that strongly absorbs radiation in the 8-11  $\mu\text{m}$  wavelength interval. A TEA CO<sub>2</sub> laser ( $\lambda = 10.6 \mu\text{m}$ ), 300 ns pulse width and 8 J pulse energy, was used for ablation of water diluted NaBF<sub>4</sub> contained in a conical aluminum nozzle. Net imparted impulse and coupling coefficient were derived from the force sensor data and are reported below.

### **Introduction**

The use of liquid ablatants for laser propulsion presents certain advantages over solid propellants. For example, the use of different ablation vessel geometries, *i.e.*, parabolic, conical, etc. can provide the optimal utilization of thrust. Another important advantage is the possibility to use solutions of varying concentration and quantity, depending on the current mission / maneuver requirements. Promising results on liquid ablatants for laser propulsion were reported, for example, in Refs. 1, 2.

It is known that Sodium Fluoroborate [NaBF<sub>4</sub>] in its solid state presents almost zero transmittance in 8  $\mu\text{m}$  to 11  $\mu\text{m}$  wavelength range, which matches the TEA CO<sub>2</sub> laser wavelength [10.6  $\mu\text{m}$ ].<sup>3</sup> This served as an incentive to investigate potentially enhanced momentum transfer of ablation of this “sensitizer” diluted in water using CO<sub>2</sub> laser pulses, since higher absorption would mean a more efficient conversion of laser pulse energy into ejected ablatant. Of course, at these wavelengths water itself is a very good absorber (Figure 1), so it would prove worthwhile to investigate if the added compound would increase momentum even further

Report Documentation Page			Form Approved OMB No. 0704-0188		
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE <b>OCT 2004</b>		2. REPORT TYPE		3. DATES COVERED -	
4. TITLE AND SUBTITLE <b>Absorption Enhanced Liquid Ablation with TEA CO2 Laser</b>				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) <b>E Sterling; A Pakhomov; C Larson; F Mead Jr.</b>				5d. PROJECT NUMBER <b>4847</b>	
				5e. TASK NUMBER <b>0159</b>	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>Air Force Research Laboratory (AFMC), AFRL/PRSP, 10 E. Saturn Blvd., Edwards AFB, CA, 93524-7680</b>				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited</b>					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT <b>A novel technique for measuring of force as a function of time was developed for the study of enhanced momentum transfer in laser-ablated water solutions of Sodium Tetrafluoroborate [NaBF<sub>4</sub>], a compound that strongly absorbs radiation in the 8-11 μm wavelength interval. A TEA CO<sub>2</sub> laser (λ = 10.6 μm), 300 ns pulse width and 8 J pulse energy, was used for ablation of water diluted NaBF<sub>4</sub> contained in a conical aluminum nozzle. Net imparted impulse and coupling coefficient were derived from the force sensor data and are reported in this paper.</b>					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES <b>7</b>	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			

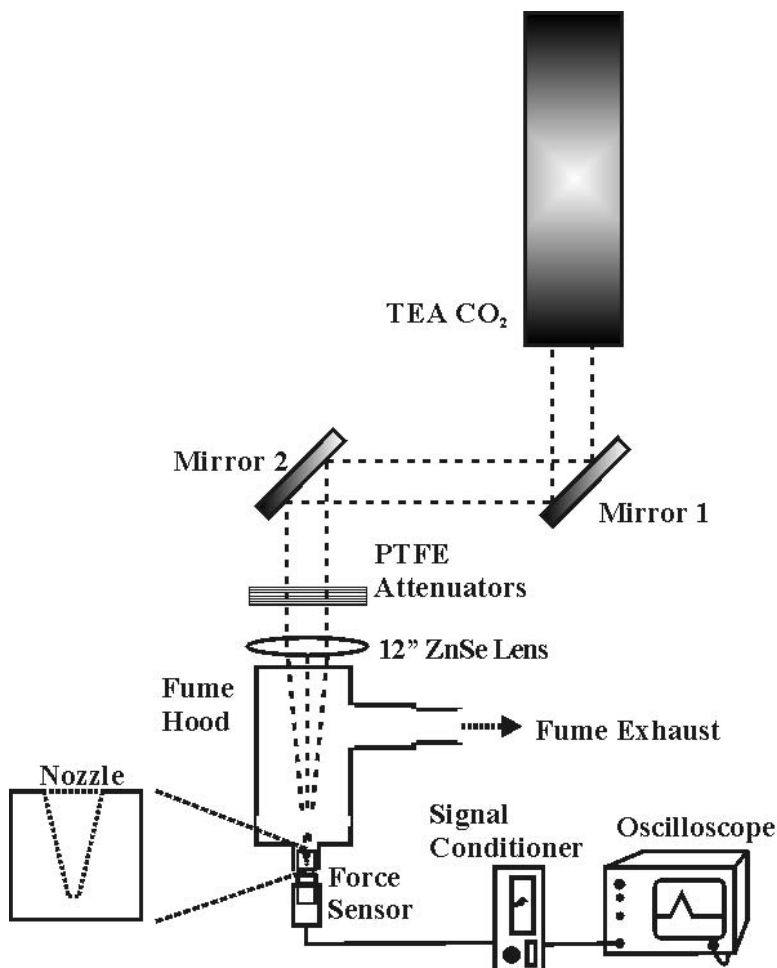


**Figure 1. Absorption spectrum of water.**

Momentum imparted to various solids has been investigated by our group in former experiments at atmospheric pressures, as well as vacuum, using a piezoelectric force sensor.<sup>4</sup> The sensor measures force imparted to the ablated surface, which in turn may be resolved temporally to obtain momentum, specific impulse and coupling coefficient ( $C_m$ ). Other techniques for measurement of these parameters, such as ion time-of-flight and time-resolved ICCD imaging have been compared with force measurements,<sup>5</sup> thus proving it to be a reliable technique.

In our early experiments we were unable to resolve the force as a function of time. For this reason, the impulse data was derived from temporal extrapolations.<sup>4</sup> In order to accomplish this study, we attempted to resolve the imparted force as a function of time. Then, if successful, we planned to derive the impulse from force waveforms by integration.

- Transverse Excited Atmospheric CO<sub>2</sub> laser [Lumonics TEA-100-2] (for detailed description of the laser output characteristics see Ref. 6).
- Pulse duration 0.3  $\mu$ s, 8 J pulse energy at 10.6  $\mu$ m wavelength.
- Laser pulse was attenuated to 0.5 J to minimize air breakdown effects on the liquid surface using polytetrafluoroethylene plates.
- Force measurements done using piezoelectric sensor PCB-209 C01 [5  $\mu$ s rise time].
- Varying molar concentrations of NaBF<sub>4</sub> were ablated from a conical nozzle cut inside an aluminum pellet [cone expansion ratio of 6]. Molarity of saturated solution was M = 10 mol/l.
- Ablatant volume kept constant at 10  $\mu$ l.
- Additional ablation experiments on pure water using Molelectron MY32-10 Nd:YAG laser. Pulse duration 15 ns, energy 200 mJ at 1064 nm wavelength.



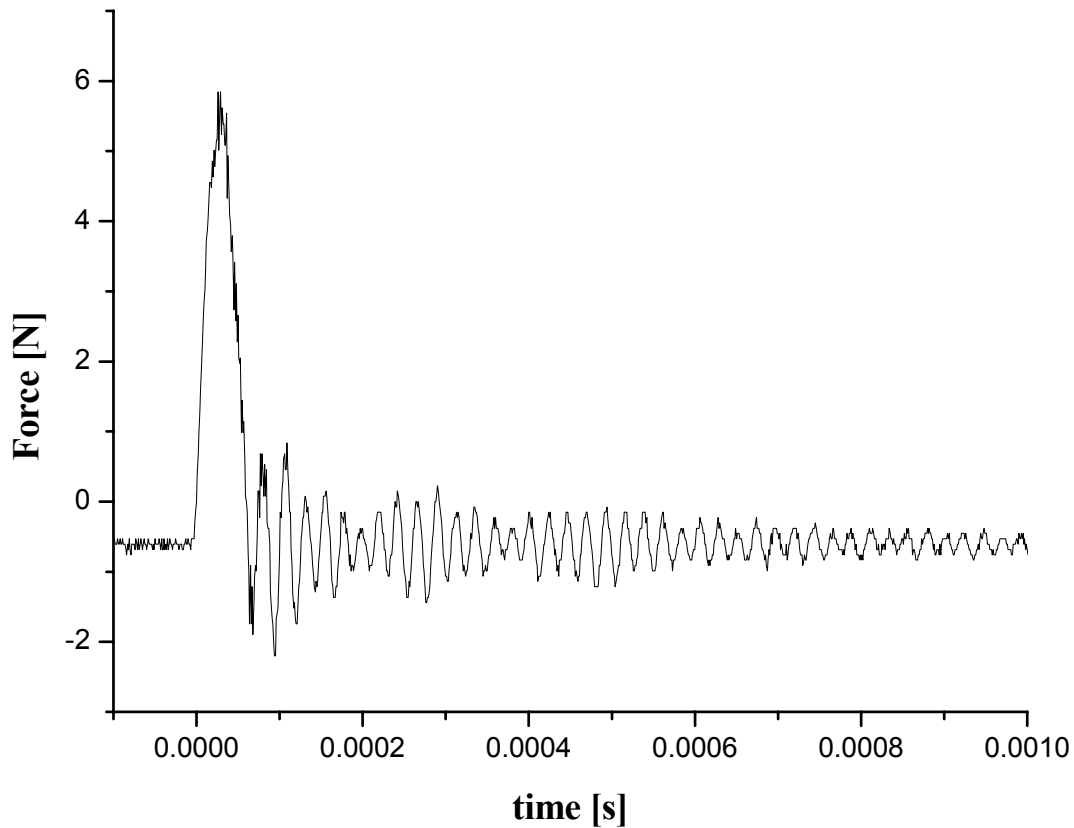
**Figure 2. Experimental setup**

## **Results and Discussion**

Momentum imparted to the aluminum nozzle was determined from the area under the curve of the force sensor readings. Coupling coefficient was then calculated by dividing momentum by laser energy (500 mJ). A typical pulse profile of force as a function of time is shown in Figure 3.

Figure 4 shows the graph for the coupling coefficient at various molar concentrations; error bars show standard deviation of the data. The  $C_m$  uncertainties are due to nozzle jitter caused by the fume hood exhaust. As the graph shows, coupling coefficient is independent of fluoroborate concentrations. Since water has a skin depth of  $\sim 5 \mu\text{m}$ , the added sensitizer produces no effect on the absorption of radiation, and hence, on the imparted momentum.

Figure 5 shows the coupling coefficient  $C_m$  as a function of water volume.  $C_m$  linearly increases with volume up to 15 ml, while above 20 ml the function reaches a plateau. It is worth noting that for all experimental points of Figure 5 the fraction of removed mass stayed relatively constant as 3/5 of initial mass.



**Figure 3.  $F(t)$  waveform.**

### Conclusions

- Direct force as a function of time waveforms were measured for the first time.
- Addition of tetrafluoroborate to the water produced no effect on the absorption of radiation, and hence, on the imparted momentum.
- Coupling coefficients on water were  $\sim 40$  dynes/W
- Further work will involve the analysis of coupling coefficient using alternate nozzle geometries and different laser wavelengths.

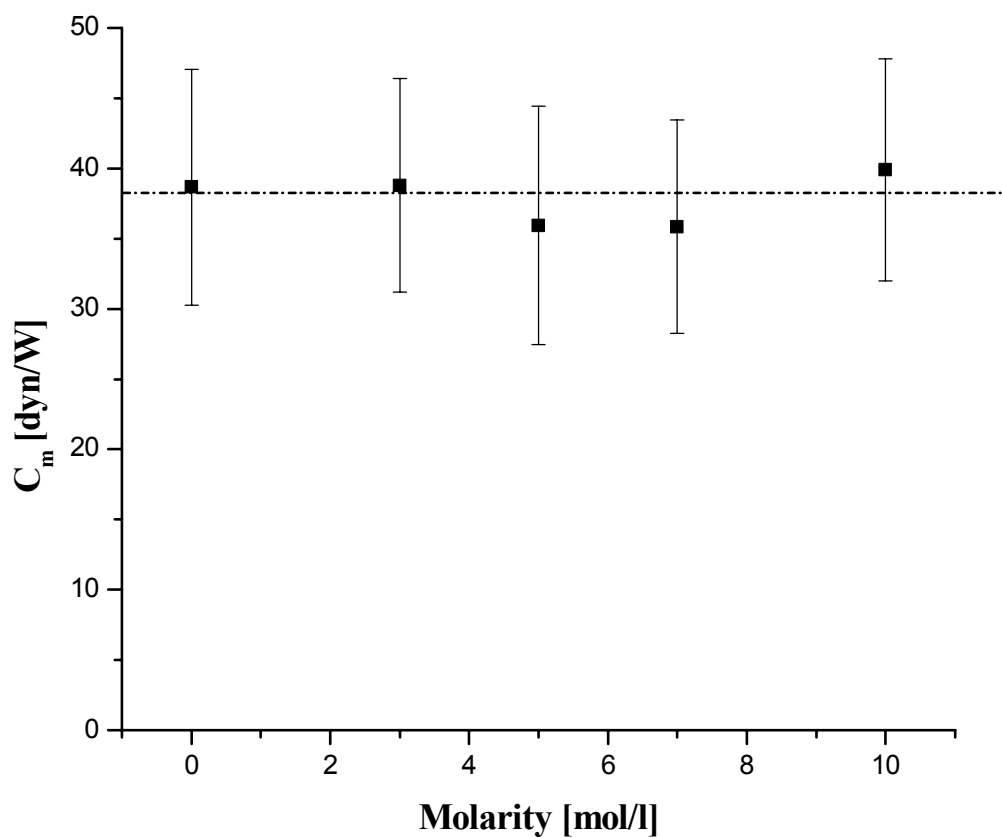
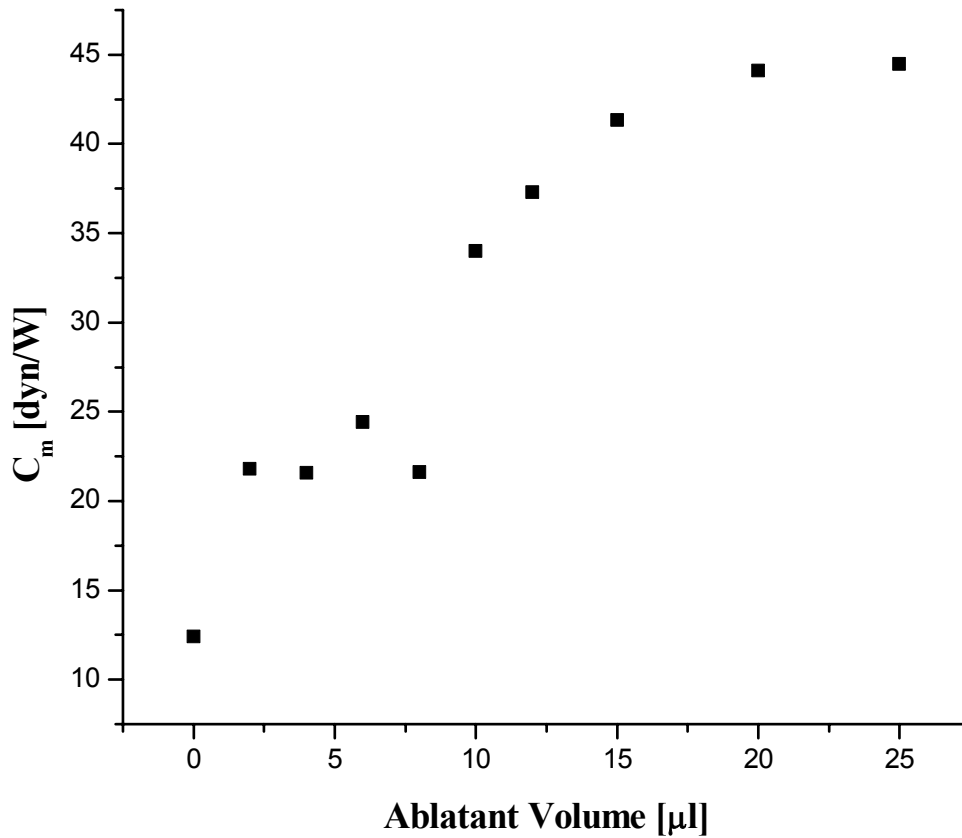


Figure 4. Coupling coefficient as a function of  $\text{NaBF}_4$  molar concentration



**Figure 5. Coupling coefficient as a function of ablatant volume**

### **Acknowledgements**

The authors would like to acknowledge discussions and suggestions provided by members of the Laser Propulsion Group at UAH.

### **References**

1. Takashi Yabe, Ryou Nakagawa, Masashi Yamaguchi, Tomomasa Ohkubo, Keiichi Aoki, Choijil Baasandash, Hirokazu Oozono, Takehiro Oku, Kazumoto Taniguchi, Masamichi Nakagawa, Masashi Sakata, Youichi Ogata and Gen Inoue, "Simulation and Experiments on Laser Propulsion by Water Cannon Target," First International Symposium on Beamed Energy Propulsion, Huntsville, Alabama, 2002, edited by Andrew V. Pakhomov, American Institute of Physics Conference Proceedings 664, 185-193 (2003).
2. Takashi Yabe, Hirokazu Ohzono, Tomomasa Ohkubo, Choijil Baasandash, Masashi Yamaguchi, Takehiro Oku, Kazumoto Taniguchi, Sho Miyazaki, Ryoze Akoh, Youichi Ogata, Benjamin Rosenberg and Minoru Yoshida, "Proposal of Liquid Cannon Target

Driven by Fiber Laser for Micro-Thruster in Satellite,” Second International Symposium on Beamed Energy Propulsion, Sendai, Japan, 2003, edited by Kimiya Komurasaki, American Institute of Physics Conference Proceedings 702, 503-512 (2004).

3. H. A. Bonadeo, E. Silberman, “The vibrational spectra of sodium, potassium and ammonium fluoroborates,” *Spectrochimica Acta* 26A, 2337-2343, (1970)

4. A.V. Pakhomov, M.S. Thompson, W. Swift, Jr., and D.A. Gregory, “Ablative Laser Propulsion: Specific Impulse and Thrust Derived from Force Measurements,” *AIAA Journal* 40, #11, 2305-2311 (2002).

5. J. Lin, M.S. Thompson and A.V. Pakhomov, “Ablative Laser Propulsion: Determination of Specific Impulse from Plasma Imaging,” 5th SPIE High-Power Laser Ablation Symposium, 25 - 30 April 2004, Taos, NM, edited by Claude Phipps, *Proceedings of SPIE* 5448, Part One, 465-476 (2004).

6. A.V. Pakhomov, J. Lin, and K.A. Herren, “Effect of air pressure on propulsion with TEA CO<sub>2</sub> laser,” 5th SPIE High-Power Laser Ablation Symposium, 25 - 30 April 2004, Taos, NM, edited by Claude Phipps, *Proceedings of SPIE* 5448, Part Two, 1017-1027 (2004).